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RARE Z DECAYS IN COMPOSITE MODELS*

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ABSTRACT

We consider several rare decays of the Z boson which are small according to the standard model but significant in composite models. These processes are likely to produce the first signals of compositeness at the new e^+e^- machines such as SLC and LEP.

The Glashow-Weinberg-Salam (GWS) model describes all electroweak phenomena quite well up to energies of the order of 100 GeV. However, it may well be that this model fails beyond these energies, so it is worthwhile to study alternative models that, explaining the low energy data, have a different high energy behavior. This exercise becomes more significant in view of the fact that the new generation of colliders will soon be operational and may detect deviations from the standard model prediction.

Among the alternatives to the standard model we shall concentrate on the so called composite models. There is a wide variety of such models and we shall study the consequences of compositeness in a model independent way. However, when reference to a specific model is required we will keep in mind one of the most promising of such theories: the strongly-coupled standard (SCS) model.^{1,2}

The Lagrangian of the SCS model is identical to that of the GWS model, the only difference being that the parameters in the scalar's potential are chosen such that the $SU(2)_L$ gauge group is not spontaneously broken but is instead confining. Therefore, all observable particles are $SU(2)_L$ singlets: the left handed quarks and leptons are fermion-boson bound states, whereas the Higgs and the intermediate vector bosons are boson-boson bound states. The weak interactions arise as the residual interaction of the $SU(2)_L$ singlets, very much the same way as the "strong interactions" arise between color singlets in QCD. In fact, the low energy effective theory of the SCS model, containing all operators of dimension four or lower, is the GWS model in unitary gauge.² At higher energy the SCS model predicts exotic states like excited vector bosons and leptons. Also the effective interactions of dimension five or higher become relevant.

In this note, we want to investigate the consequences of such higher dimension operators in the physics of Z -decays, which might be observed in the new e^+e^- machines such as SLC. We examine four decays into "standard" GWS-model particles in detail: $Z \rightarrow \gamma H$, $Z \rightarrow \gamma HH$, $Z \rightarrow \nu\bar{\nu}\gamma$ and $Z \rightarrow \nu\bar{\nu}H$. The first three reactions

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occur in the GWS model only at the one loop level, the last process is given by a tree diagram.

These reactions were chosen for the following reasons: we looked for n body final states with $n \leq 3$ since for $n > 3$ phase space renders the process unobservable, also we required the effective vertex for each reaction to be of dimension ≤ 6 . For dimension > 6 vertices the rates become negligible due to phase space and/or due to our assumption that each photon couples via the operator $eF_{\mu\nu}$ (see below). Other reactions are either forbidden or uninteresting, for example, the SCS model reproduces the standard model coupling to fermion pairs, as any model should, so there is nothing new to learn: $Z \rightarrow \gamma\gamma$ and $Z \rightarrow HH$ are forbidden by angular momentum conservation and Bose symmetry. The lowest dimension operator mediating $Z \rightarrow \gamma\gamma H$ which respects the $U(1)$ gauge invariance is of dimension seven, therefore, we disregard it.

In order not to restrict ourselves to a specific model we write down the most general, lowest dimension operators which yield a given decay. Naturally, we require that these couplings respect the electromagnetic $U(1)$ gauge invariance. For each photon in an operator we contribute a factor of e . We assume that the other coupling "constants" which are in fact products of constants and form factors, are of order one. From the strong interaction point of view this seems to be a reasonable assumption (so far experimentally, only one of these effective couplings in the SCS model can be determined:² the W -fermion-fermion coupling $\bar{g}$ which is found to be $\bar{g} \simeq 0.66$). We also do not know precisely the scale Λ characterizing the $SU(2)_L$ interactions, but it must be of the order $G_F^{1/2} \sim 300$ GeV and could be as low as 100 GeV.

The usual point electromagnetic interaction $4\pi\alpha^2/3s$ is already very small at 90 GeV (namely 10^{-35} cm^2). In order to get a measurable rate at SLC we therefore propose to look for the rare Z decays precisely at the Z production pole. We assume a SLC luminosity of $10^{30} \text{ cm}^{-2} \text{ s}^{-1}$ and hope that SLC will run at the Z pole for about a third of a year (i.e. 10^7 seconds). Therefore, cross sections for $e^+e^- \rightarrow Z \rightarrow \gamma H$, $\gamma H H$, $\nu\nu H$, $\nu\nu\gamma$ will be observable if they are at least 10^{-36} cm^2 (corresponding to about 10 events in 10^7 seconds). The cross-sections can be easily determined using the respective widths and the standard Breit-Wigner resonance formula:

$$\sigma(e^+e^- \rightarrow Z \rightarrow \text{rare}) = \frac{12\pi}{M^2} B(Z \rightarrow e^+e^-) B(Z \rightarrow \text{rare}) \quad (1)$$

where M is the mass of the Z boson, $B(Z \rightarrow e^+e^-)$ the branching ratio of Z into electrons (about 3%) and

$$B(Z \rightarrow \text{rare}) = \frac{\Gamma(Z \rightarrow \text{rare})}{\Gamma(Z \rightarrow \text{anything})} \simeq \frac{\Gamma(Z \rightarrow \text{rare})}{2.8 \text{ GeV}}$$

$Z \rightarrow \gamma H$

The lowest dimension (= five) operator mediating this decay is:

$$\mathcal{L}_{\text{int}} = \frac{e}{\Lambda} (\bar{\kappa}_1 F_{\mu\nu} + \bar{\kappa}_2 {}^*F_{\mu\nu}) Z^{\mu\nu} H \quad (2)$$

Fig. 1: Cross section for the reaction $e^+e^- \rightarrow Z \rightarrow \gamma H$ as a function of the Higgs' mass, for two values of Λ and for the standard model at $s = M^2$. The expected SLC rates are also indicated.

where ${}^*F_{\mu\nu} = \frac{1}{2}\epsilon_{\mu\nu\rho\sigma}F^{\rho\sigma}$, $Z_{\mu\nu} = \partial_\mu Z_\nu - \partial_\nu Z_\mu$, and Λ is the scale of the $SU(2)_L$ interactions. Notice that the piece proportional to $\bar{\kappa}_1$ is CP conserving whereas the one proportional to $\bar{\kappa}_2$ is CP violating. The decay width is easily calculated to be

$$\Gamma(Z \rightarrow \gamma H) = \frac{\alpha}{6} (\bar{\kappa}_1^2 + \bar{\kappa}_2^2) \left(\frac{M}{\Lambda} \right)^2 M \left(1 - \frac{m^2}{M^2} \right)^3 \quad (3)$$

M and m being the masses of the Z and the Higgs, respectively. Note that the CP conserving and CP violating pieces in $\mathcal{L}_{\text{int}}$ give both the same amplitude.

This process has a very clear signature: having produced the Z on resonance in an e^+e^- collider it will be at rest, so one will detect a monochromatic photon of energy $E_\gamma = (M^2 - m^2)/2M$ recoiling against two heavy quark jets (the main decay products of H). The same decay in the standard model is given by a loop diagram (this contribution occurs also in the SCS model, as it contains all the basic GWS model couplings, however, we do not include it in Eqs. (2) and (3) since it is negligible, see below) which has been calculated by Cahn, Chanowitz and Fleishon.³ In Fig. 1 we present the cross section $\sigma(e^+e^- \rightarrow Z \rightarrow \gamma H)$ as a function at $s = M^2$, we give our result for $\bar{\kappa}_1^2 + \bar{\kappa}_2^2 = 1$ and $\Lambda/M = 1, 3$, as well as the standard model prediction from Ref. [3]. We see that Eq. (2) gives a much higher cross section than the standard model does, even for a Higgs mass of order 80 GeV and $\Lambda = 3M$ one should be able to see more than 10 events in 10^7 seconds running time.

Fig. 2: Cross section for the reaction $e^+e^- \rightarrow Z \rightarrow \gamma HH$ as a function of the Higgs' mass, for two values of Λ , at $s = M^2$. The expected SLC rates are also indicated.

$$Z \rightarrow \gamma HH$$

Here the lowest dimension operator is given by

$$\mathcal{L}_{\text{int}} = \frac{1}{2} \frac{e}{\Lambda^2} (\lambda_1 F_{\mu\nu} + \lambda_2 {}^*F_{\mu\nu}) Z^{\mu\nu} H^2. \quad (4)$$

Again, the piece proportional to λ_1 (λ_2) is CP conserving (violating): both give the same amplitude. After evaluating some grim phase space integrals we obtain for the width

$$\Gamma(Z \rightarrow \gamma HH) = \frac{\alpha}{96\pi^2} (\lambda_1^2 + \lambda_2^2) \left(\frac{M}{\Lambda}\right)^4 M \left[\left(\frac{1}{4} + \frac{13}{24}\mu - \frac{31}{96}\mu^2 + \frac{15}{192}\mu^3\right) \sqrt{1-\mu} + \left(-\mu + \frac{3}{4}\mu^2 - \frac{3}{8}\mu^3 + \frac{5}{64}\mu^4\right) \tanh^{-1} \sqrt{1-\mu} \right] \quad (5)$$

where $\mu \equiv (2m/M)^2$. In Fig. 2 we show $\sigma(e^+e^- \rightarrow Z \rightarrow \gamma HH)$ as a function of the Higgs mass, again we take $(\lambda_1^2 + \lambda_2^2) = 1$ having no better guess, and $\Lambda/M = 1, 3$. Unfortunately σ is, even for small Higgs mass, not very big: this process could only be observed at SLC if $\Lambda \sim M$ and if m is smaller than 20 GeV.

In the standard model, $Z \rightarrow \gamma HH$ occurs via a loop diagram (basically the same as for $Z \rightarrow \gamma H$, with one additional Higgs vertex). For light Higgs bosons

Fig. 3: Cross section for the reaction $e^+e^- \rightarrow Z \rightarrow \nu\bar{\nu}\gamma$ as a function of E_{min} , for two values of Λ and for the standard model. σ was calculated at $s = M^2$ for three rapidity cuts. The expected SLC ratio is also indicated.

the corresponding width can be estimated to be a factor of 2×10^{-2} smaller than $\Gamma(Z \rightarrow \gamma H)$ so that its contribution is negligible compared to the one coming from Eq. (4).

$$Z \rightarrow \nu\bar{\nu}\gamma.$$

The lowest dimension operator for this decay is given by

$$\mathcal{L}_{\text{int}} = \frac{e}{\Lambda^2} (\kappa_1 F_{\mu\nu} + \kappa_2 {}^*F_{\mu\nu}) \bar{\psi}\gamma^\mu(a + b\gamma_5)\psi \cdot Z^\mu \quad (6)$$

Here the piece proportional to κ_2 (κ_1) is CP even (odd), and again both terms give the same amplitude. The differential decay width is given by

$$\frac{d\Gamma}{dx} = \frac{\alpha}{96\pi^2} (\kappa_1^2 + \kappa_2^2) (a^2 + b^2) \left(\frac{M}{\Lambda}\right)^4 M \left(\frac{2}{3}x^3 - \frac{1}{3}x^4\right) \quad (7)$$

where x is proportional to the photon energy: $x = 2E_\gamma/M$. From Eq. (7) we easily derive

$$\Gamma(x_0) \equiv \int_{x_0}^1 \frac{d\Gamma}{dx} dx = \frac{\alpha}{96\pi^2} (\kappa_1^2 + \kappa_2^2) (a^2 + b^2) \left(\frac{M}{\Lambda}\right)^4 M \left(\frac{1}{10} - \frac{1}{6}x_0 + \frac{1}{15}x_0^5\right) \quad (8)$$

i.e., the width of $Z \rightarrow \gamma\nu\bar{\nu}$ for which the photon has an energy $E_{\text{min}} = (1/2)Mx_0$ or greater. In Fig. 3 we plot the cross section for $e^+e^- \rightarrow Z \rightarrow \nu\bar{\nu}\gamma$ against E_{min} at $s = M^2$. Again, we have chosen $\Lambda/M = 1, 3$ and $(\kappa_1^2 + \kappa_2^2) (a^2 + b^2) = 1$ and we also assume the presence of three contributing neutrinos.

The process $Z \rightarrow \nu\bar{\nu}\gamma$ occurs in the standard model only via a one loop diagram and is therefore small. But there is considerable standard model background coming from $e^+e^- \rightarrow \nu\bar{\nu}\gamma$. In fact, the reactions proposed to count the number of different massless neutrinos⁴ have the same signature. It is important to note that these counting experiments are to be performed at energies above the Z peak and not on top of the resonance. At $s = M^2$ this contribution is considerably smaller, as can be seen in Fig. 3 where we also plotted the standard model prediction for $\sigma(e^+e^- \rightarrow \nu\bar{\nu}\gamma)$.⁴ For high enough E_{min} the contribution from Eq. (6) will dominate, and for Δ/M small one should definitely observe this process, especially given that its signature is very clear: only a single photon and missing energy.

$$Z \rightarrow \nu\bar{\nu}H.$$

Here the lowest dimension operator is given by

$$\mathcal{L}_{\text{int}} = \frac{\lambda}{\Lambda} Z^\mu \bar{\psi} \gamma_\mu (a + b\gamma_5) \psi \cdot H \quad (9)$$

The width is easily computed to be

$$\Gamma(Z \rightarrow \nu\bar{\nu}H) = \frac{1}{144 \cdot (4\pi)^3} \lambda^2 (a^2 + b^2) \left(\frac{M}{\Lambda}\right)^2 \times M [(36\bar{\mu}^2 + 48\bar{\mu}^2) \ln \bar{\mu} - \bar{\mu}^4 - 72\bar{\mu}^2 + 64\bar{\mu} + 9] \quad (10)$$

where $\bar{\mu} = m^2/M^2$. This can be compared with the standard model prediction, given by the obvious tree diagram. Using the standard Feynman rules (see, for example, Ref. [5]) we find

$$\Gamma(Z \rightarrow \nu\bar{\nu}H) = \frac{2\alpha^2}{49\pi \sin^4(2\theta_W)} \left\{ \frac{\bar{\mu} - 1}{6} (2\bar{\mu}^2 - 13\bar{\mu} + 47) - \frac{1}{2} (\bar{\mu}^2 - 6\bar{\mu} + 4) \ln \bar{\mu} + \sqrt{\frac{\bar{\mu}}{4 - \bar{\mu}}} (\bar{\mu}^2 - 8\bar{\mu} + 20) \left[\tan^{-1} \frac{2 - \bar{\mu}}{\sqrt{\bar{\mu}(4 - \bar{\mu})}} - \tan^{-1} \sqrt{\frac{\bar{\mu}}{4 - \bar{\mu}}} \right] \right\} \quad (11)$$

In Fig. 4 we compare the cross sections corresponding to Eqs. (10) and (11). In Eq. (10) we have set, as usual, $\lambda^2(a^2 + b^2) = 1$ and $\Delta/M = 1, 3$. Unfortunately, the standard model prediction is bigger than the contribution expected from Eq. (9). Since all the standard model couplings are also present in the SCS model, we should add up the contributions from Eq. (9) and the standard model coherently. Still, this is expected to change Eq. (11) by a small amount unless Δ/M is unreasonably small, so we conclude that this particular reaction is not especially useful in determining whether there is compositeness.

Of the four reactions we have studied, two seem particularly well-suited to determine the effects of possible compositeness. The reaction $Z \rightarrow \gamma H$ is not very sensitive to changes in Δ/M , so even for Δ/M big there is a change of seeing this process. The major drawback of this reaction is that the Higgs might be heavier than the Z , in

Fig. 4: Cross sections for the reaction $e^+e^- \rightarrow Z \rightarrow \nu\bar{\nu}H$ as a function of the Higgs' mass, for two values of Δ and for the standard model at $s = M^2$. The composite cross section comes only from Eq. (9). Also, the expected SLC rates are indicated.

which case it would be kinematically forbidden. (There are essentially no experimental limits on the mass of the neutral Higgs boson). Unfortunately, the SCS model favors a ratio for Δ/M of approximately five, but for Δ/M not too big we expect that the first signs of compositeness (if this concept is correct) could be observed at SLC also in the reaction $Z \rightarrow \nu\bar{\nu}\gamma$. This process has a very conspicuous signature, and it should be very easy to trigger on it for high enough photon energies.

Composite models could lead to very exciting physics observable already in the first year of operation of SLC at full luminosity. With respect to the SCS model, the issue at hand is: "How is the standard model realized?" As a confining or a spontaneously broken gauge theory? Measurement of $e^+e^- \rightarrow H\gamma$ and $e^+e^- \rightarrow \nu\bar{\nu}\gamma$ at the Z peak might give us a clue.

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